Egyptian Journal of Aquatic Biology and Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(6): 503 – 524 (2025)
www.ejabf.journals.ekb.eg

Ecological Assessment of Mangrove Community Structure and Habitat Quality in Perupuk Village, North Sumatra, Indonesia

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ARTICLE INFO
Article History:
Received: Aug. 7, 2025
Accepted: Sep. 25, 2025
Online: Nov. 14, 2025

Keywords:
Species diversity,
Coastal vegetation,
Ecosystem evaluation,
Perupuk,
Environmental condition

ABSTRACT
Mangrove forests are highly productive intertidal ecosystems that provide vital ecological services, including shoreline stabilization, sediment retention, carbon sequestration, nutrient cycling, and nursery grounds for aquatic organisms. However, these ecosystems are increasingly threatened by land-use change, aquaculture expansion, and anthropogenic pressures. This study evaluates the mangrove community structure and habitat quality in Perupuk Village, North Sumatra, to characterize species composition, vegetation attributes, and ecosystem condition. Field surveys conducted at four stations identified nine true mangrove species from four families, dominated by *Avicennia officinalis* and *Rhizophora apiculata*. Species density ranged from 1,700 to 4,400 ind ha^{-1}, with the highest value recorded at Station 4, reflecting favorable environmental conditions and strong regeneration potential. The importance value index (IVI) analysis revealed the ecological dominance of *A. officinalis* across most stations and substrate-driven prevalence of *R. apiculata* in estuarine zones. Habitat quality assessment using the modified US-EPA (1999) protocol yielded total scores between 31 and 35, classifying all stations as sub-optimal due to sediment deposition, turbidity, and human disturbance despite suitable pH, salinity, and muddy substrates. Spatial analysis based on Sentinel-2A NDVI classification indicated a total mangrove area of 45.17 ha, with 44% categorized as high-density vegetation, while sparse zones remain susceptible to degradation. This study aims to assess the structure and habitat quality of mangrove communities to provide ecological baseline information for sustainable mangrove management in Perupuk Village, North Sumatra.

INTRODUCTION

Mangrove forests are highly productive intertidal ecosystems that perform essential ecological functions for tropical coastlines, including shoreline protection, sediment stabilization, carbon sequestration, nutrient retention, and serving as nursery habitats for fishes and invertebrates. These services are fundamental for both biodiversity conservation and the livelihoods of millions of coastal inhabitants, yet they are increasingly threatened by land-use change and anthropogenic pressures. As it was emphasized by **Macreadie *et al.* (2019)**, the blue carbon value and co-benefits of mangrove ecosystems make them critical targets for conservation and climate mitigation, requiring robust ecological monitoring and management.

Despite their ecological significance, mangroves have undergone extensive degradation worldwide. Global estimates indicate losses of nearly one million hectares since 1990, with Southeast Asia showing the highest rates of deforestation, mainly due to aquaculture development, agriculture, and urbanization **(Richards & Friess 2016; Goldberg *et al.*, 2020)**. Indonesia, which contains the world's largest mangrove area at approximately 3.36 million hectares, or nearly 19% of the global total, has experienced notable declines in the past decade. National evaluations reveal that the country lost an average of 12,818 hectares per year between 2009 and 2019 **(Arifanti *et al.*, 2022)**. While, regional reports indicate a rate of 21,100 hectares per year between 2010 and 2020 **(FAO, 2020)**. Such losses have reduced biodiversity, altered habitat quality, and weakened ecosystem services, limiting the resilience of coastal communities **(Murdiyarso *et al.*, 2015)**.

The structural integrity of mangrove stands determines their ecological functions and long-term sustainability. Healthy forests are characterized by high species richness, balanced diameter distribution, and active regeneration, whereas poor regeneration and skewed dominance patterns often signal ecological stress and degradation **(Alongi, 2020)**. For this reason, analysis of mangrove community structure through parameters such as relative density, relative frequency, and importance value index (IVI) is an effective means of evaluating habitat condition and identifying areas at risk of further decline.

In North Sumatra, mangrove cover has diminished significantly in recent decades, with approximately 34,063 ha lost between 1990 and 2020, primarily due to agricultural expansion and aquaculture **(Ginting *et al.*, 2022)**. At the local scale, Lima Puluh Pesisir District, where Perupuk Village is situated, mangrove cover declined from 552.47 hectares in 2013 to 315.63 hectares in 2022, representing a reduction of 42.9%. This reduction has been accompanied by shoreline retreat, fragmentation, and loss of habitat quality. In several coastal sections, shoreline erosion exceeded 30 meters in less than a decade, placing additional pressure on both ecological integrity and community safety. Given these conditions, Perupuk has become a focal area for rehabilitation and conservation programs, making it a critical site for evaluating mangrove ecosystem structure and habitat quality **(Rumondang *et al.*, 2024)**.

This study aims to assess the mangrove community structure and habitat condition in Perupuk Village, North Sumatra, through field-based ecological surveys and quantitative analysis of vegetation attributes. By documenting species composition, tree density, basal area, diversity indices, and regeneration patterns, this research establishes a scientific baseline for monitoring future changes, guiding conservation priorities, and supporting evidence-based decision-making for mangrove management in the region.

MATERIALS AND METHODS

1. Time and study location

The study took place in Perupuk Village, Batu Bara Regency, North Sumatra, Indonesia (≈3.28°N; 99.48°E) from May–July 2025, a period with stable hydro-ecological conditions suited for establishing baseline mangrove characteristics. This ecological survey represents the biophysical phase of a broader multi-stage research program, with results serving as baseline data for future co-management and stakeholder assessments. Perupuk lies on the eastern coast of Sumatra facing the Malacca Strait, has a tropical climate (>2,000 mm annual rainfall), and supports 7,754 residents across 13 hamlets whose livelihoods rely on fisheries, aquaculture, agriculture, and mangrove-based ecotourism through the Batu Bara Mangrove Park.

Four sampling stations were chosen (Fig. 1). Stations 1 and 2, within the Mangrove Park ecotourism zone, are dominated by *Rhizophora* and *Avicennia* species, respectively, with Station 1 showing strong regeneration linked to rehabilitation efforts. Stations 3 and 4 are outside the ecotourism area near rural settlements, both dominated by *Avicennia* stands. Station 4 represents an erosion-prone coastline, selected to capture mangrove structure under physical disturbance. All stations exhibit muddy substrates favorable for root development and natural regeneration.

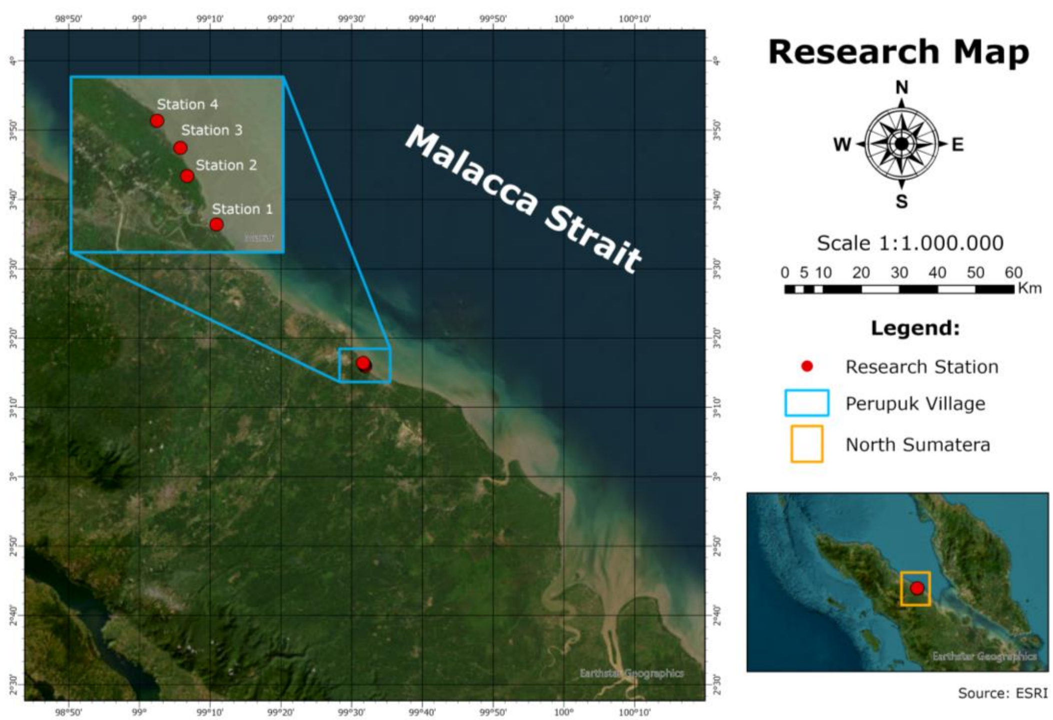

Fig. 1. Map of research location

2. Materials and equipment

The materials and equipment used for fieldwork and data collection are summarized in Table (1). They were essential for measuring mangrove structural attributes, recording environmental parameters, and supporting habitat assessment in Perupuk Village.

Table 1. Materials and equipment used

Equipment/Material	Function
GPS	Determination of Sampling Points
Camera	Documentation Collection
Measuring Tape	Measurement of Tree Circumference and Transect Line
pH Meter	Measurement of Water and Sediment pH
Plastic Rope	Transect Establishment
Thermometer	Measurement of Water Temperature

3. Sampling techniques and identification

Mangrove data were collected using a line-transect plot method, with one transect per station and three 10 × 10 m plots along each transect. This design follows rapid ecological assessment principles to ensure consistent sampling effort and representation of stand structure across stations. In each plot, all mangrove species were identified, enumerated, and measured to determine density, frequency, and importance value index (IVI). Diameter at breast height (DBH, 1.3 m) was measured for trees, while seedlings and saplings were recorded in nested 1 × 1 m and 5 × 5 m sub-plots, respectively **(English *et al.*, 1997; Noor *et al.*, 2006**). Habitat conditions were assessed through *in-situ* measurements of temperature, pH, salinity, and organic matter. Habitat quality scoring followed the **US-EPA protocol (1999)** modified by **Sudarso (2013)**, including parameters such as canopy cover, tree density, height, diameter, vegetation type, substrate, root system, and tidal regime, with scores from 1 to 4 classifying sites into optimal, sub-optimal, marginal, or poor categories. Four stations were selected—two in tourism zones and two near residential areas—to represent varying anthropogenic pressures. Mangrove condition categories were referenced to density criteria in the Minister of Environment Decree No. 201/2004. Species were identified *in situ* based on key morphological characteristics across growth stages using the Indonesian mangrove field guides (**Noor *et al.*, 2006; Djamaluddin, 2024**).

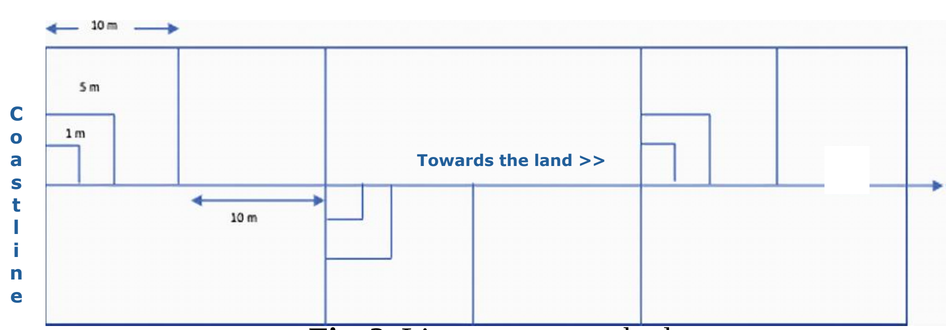

Fig. 2. Line transect method
(Rumondang *et al.*, 2023)

4. Data analysis

a) Relative density

Relative density (RDi) is the ratio between the number of individuals of a mangrove species and the total number of individuals of all species within a unit area, expressed as a percentage. Relative density is used to determine the contribution of each species to the overall mangrove community within an ecosystem. The relative density can be calculated using the following formula:

$$RDi = \frac{Di}{\sum Di} x100$$

Where, RDi is the relative density expressed in percent, Di refers to the density of species *i*, and ∑Di represents the total density of all species recorded within the sampling area. Relative density provides a quantitative measure of the contribution of each mangrove species to the overall community structure, allowing for comparison of species dominance and distribution patterns across sampling stations.

b) Relative frequency

Relative frequency (RFi) is the percentage ratio between the frequency of a mangrove species and the total frequency of all species within an observation area. This parameter is used to assess how often a species is found compared to others in the mangrove community and provides an overview of species dominance and distribution patterns. The relative frequency can be calculated using the following formula:

$$RFi = \frac{Fi}{\sum Fi} x100$$

Where, RFi is the relative frequency expressed in percent, Fi refers to the frequency of species i, and ∑F represents the total frequency of all species recorded within the sampling area. Relative frequency provides an index of how consistently each mangrove species occurs across sampling plots, reflecting its spatial distribution and ecological dominance within the community.

d) Importance value index (IVI)

The importance value index (IVI) is an index used to estimate or assess the condition, state, or characteristics of a mangrove ecosystem. The importance value index (IVI) can be calculated using the following formula:

$$INP = RDi + RFi + RCi$$

Where, INP is the importance value index; RDi refers to the relative density of each species; RFi denotes the relative frequency of each species; and RCi represents the relative cover of each species. The importance value index (INP) provides a comprehensive quantitative measure of the ecological dominance of mangrove species by integrating their density, frequency, and canopy cover, thereby reflecting the overall structural and functional role of each species within the mangrove community.

e) Shannon–Wiener diversity index (H') and evenness index (J')

The Shannon–Wiener diversity index (H′) was used to quantify mangrove species diversity at each sampling station, where $H' = -\Sigma(pi \ln pi)$ and pi represents the proportion of individuals belonging to species i relative to the total number of individuals. According to **Shannon (1948)**, this index is suitable for ecological community analysis because it accounts for both species abundance and richness. Species evenness was evaluated using the Pielou evenness index (J′), calculated as $J' = H'/\ln S$, where S denotes the total number of species observed. According to **Pielou (1966)**, the J′ index measures the distribution uniformity of individuals among species, with values approaching 1 indicating a more even community structure. Diversity categories followed **Odum (1971)**, where $H' < 1$ indicates low diversity, 1–3 denotes moderate diversity, and >3 indicates high diversity.

f) Quality of water and substrat data collection

Water quality parameters measured at each sampling station included temperature, pH, and salinity. Temperature was measured using a thermometer, salinity using a hand refractometer, and pH using a portable pH meter. These parameters were assessed *in situ* to characterize the physicochemical conditions influencing mangrove distribution, physiological performance, and habitat suitability in Perupuk Village. Substrate characteristics were obtained from secondary data reported by **Rumondang *et al.* (2023)**. These data provide supporting information on sediment texture and composition, which affect substrate stability, nutrient dynamics, and the establishment of mangrove root systems within the study area.

g) Habitat quality assessment and mangrove area coverage analysis

The assessment integrated field-based habitat evaluation with GIS-based mangrove area analysis to characterize mangrove ecosystems in Perupuk Village. Habitat quality followed the **US-EPA (1999)** scoring system across four stations, assessing canopy cover, mangrove density, tree morphometrics, vegetation structure, substrate, root systems, hydrological regime, sediment conditions, and anthropogenic influence, alongside *in-situ* measurements of temperature, pH, and salinity. Water and soil parameters were emphasized due to their influence on mangrove productivity, zonation, and nutrient cycling (**Kathiresan, 2012; Alongi, 2015**). Each criterion was scored on a 1–4 scale, categorizing habitat status from poor to excellent. GIS analysis using ArcGIS Pro and Sentinel-2A imagery applied NDVI to delineate mangrove cover, validated by field ground-truthing. Spatial overlay linked habitat scores with vegetation distribution, producing ecosystem condition maps with score ranges of 11–44 and precise area estimates. Integrated remote-sensing and field data improved ecological assessment accuracy (**Hamilton & Casey, 2016**).

RESULTS

1. Composition of mangrove species

Nine mangrove species were identified in Perupuk Village, consisting of *Avicennia alba, Avicennia marina, A. officinalis, Bruguiera cylindrica, Bruguiera gymnorrhiza, R. apiculata, Rhizophora mucronata, Rhizophora stylosa*, and *Xylocarpus granatum* (Table 2). These species belong to four families, namely Acanthaceae, Rhizophoraceae, Lythraceae, and Meliaceae. The genus *Rhizophora* was the most dominant, followed by *Avicennia*, while *X. granatum* was the least represented across the study plots.

Table 2. Taxonomic classification of mangrove species in Perupuk Village

Class	Order	Family	Species
Magnoliopsida	Lamiales	Acanthaceae	*Avicennia alba*
		Acanthaceae	*Avicennia marina*
		Acanthaceae	*Avicennia officinalis*
	Malpighiales	Rhizophoraceae	*Bruguiera cylindrica*
		Rhizophoraceae	*Bruguiera gymnorrhiza*
		Rhizophoraceae	*Rhizophora apiculata*
		Rhizophoraceae	*Rhizophora mucronata*
		Rhizophoraceae	*Rhizophora stylosa*
	Sapindales	Meliaceae	*Xylocarpus granatum*

2. Species density

Four mangrove species were recorded at this site, namely *A. marina*, *R. apiculata*, *R. mucronata*, and *R. stylosa*. *R. apiculata* exhibited the highest density with 3,800 ind ha^{-1}, while *R. stylosa* showed the lowest density with 1,700 ind ha^{-1}. *A. marina* and *R. mucronata* had densities of 2,000 ind ha^{-1} and 2,100 ind ha^{-1}, respectively (Fig. 3). The mean density of mangroves at this site was approximately 2,400 ind ha^{-1}. The dominance of *R. apiculata* indicates that the muddy estuarine substrate is favorable for *Rhizophora*, whose stilt root system enhances sediment stabilization and tolerates tidal inundation **(Asante *et al.*, 2023)**. This pattern reflects a naturally regenerating stand with strong recruitment potential.

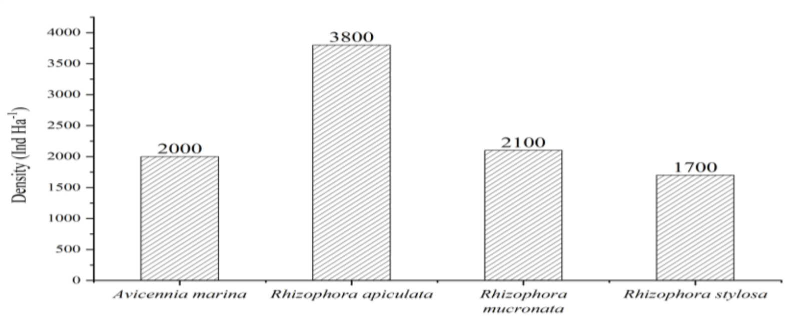

Fig. 3. Mangrove density at Station 1

At Station 2, five mangrove species were recorded at this site, namely *A. alba, A. marina, A. officinalis, R. apiculata,* and *R. stylosa*. *A. officinalis* exhibited the highest density with 3,800 ind ha^{-1}, while *R. stylosa* showed the lowest density with 1,000 ind ha^{-1}. *A. alba, A. marina,* and *R. apiculata* had densities of 1,600 ind ha^{-1}, 1,900 ind ha^{-1}, and 1,900 ind ha^{-1}, respectively (Fig. 4). The mean density of mangroves at this site was approximately 1,860 ind ha^{-1}. The predominance of *A. officinalis* suggests its ecological plasticity, as *Avicennia* species are considered pioneer taxa capable of colonizing disturbed or transitional habitats **(Hanggara *et al.*, 2021)**. The relatively balanced distribution between *Avicennia* and *Rhizophora* reflects an ecotone where both natural and anthropogenic influences shape community structure.

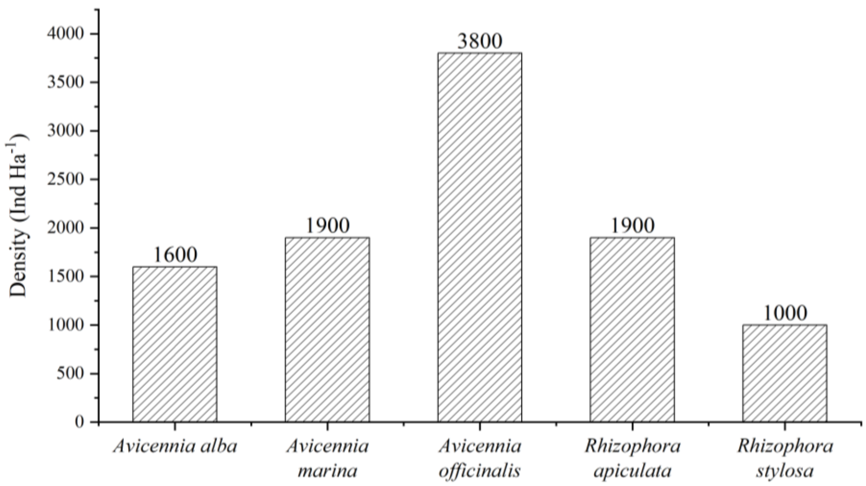

Fig. 4. Mangrove density at Station 2

At Station 3, seven mangrove species were recorded at this site, namely *A. alba*, *A. marina*, *A. officinalis*, *B. cylindrica*, *R. apiculata*, *R. mucronata*, and *R. stylosa*. *A. officinalis* exhibited the highest density with 3,600 ind ha^{-1}, while *R. mucronata* showed the lowest density with 200 ind ha^{-1}. *A. alba* and *A. marina* had relatively high densities of 2,500 ind ha^{-1} and 2,300 ind ha^{-1}, respectively, followed by *R. stylosa* with 1,700 ind ha^{-1}, *R. apiculata* with 1,300 ind ha^{-1}, and *B. cylindrica* with 600 ind ha^{-1} (Fig. 5). The mean density of mangroves at this site was approximately 1,740 ind ha^{-1}. The strong dominance of *Avicennia* species demonstrates their tolerance to intermediate salinity and reduced sediment oxygen levels, conditions that often limit the growth of *Rhizophora* **(Hijbeek *et al.*, 2013)**. Their rapid propagule dispersal also makes them highly competitive colonizers in post-disturbance environments.

At Station 4, species richness was the highest, with eight mangrove species recorded at this site, namely *A. alba*, *A. marina*, *A. officinalis*, *B. cylindrica*, *B. gymnorrhiza*, *R. apiculata*, *R. stylosa*, and *X. granatum*. *A. officinalis* exhibited the highest density with 4,400 ind ha^{-1}, while *B. gymnorrhiza* showed the lowest density with 300 ind ha^{-1}. *A. alba* and *R. stylosa* had relatively high densities of 3,300 ind ha^{-1} and

3,100 ind ha^{-1}, respectively, followed by *X. granatum* with 2,500 ind ha^{-1}, *A. marina* with 1,800 ind ha^{-1}, *R. apiculata* with 1,700 ind ha^{-1}, and *B. cylindrica* with 1,300 ind ha^{-1} (Fig. 6). The mean density of mangroves at this site was approximately 2,050 ind ha^{-1}. This station exhibited both high density and high diversity, suggesting a more structurally complex stand with active regeneration. Such mixed assemblages, where pioneers *Avicennia* coexist with *Rhizophora* and *Bruguiera*, are often associated with more stable sedimentary environments and lower exploitation pressure **(Krauss, *et al.*, 2014)**.

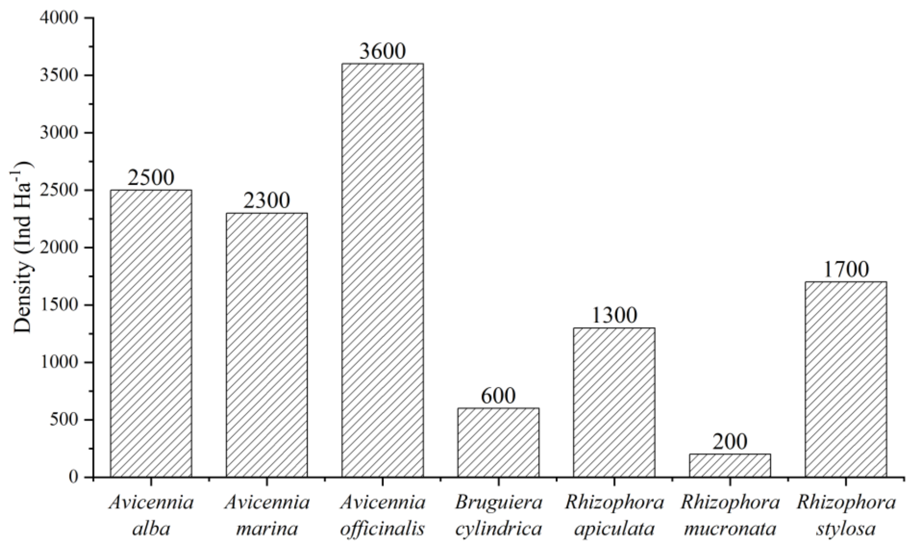

Fig. 5. Mangrove density at Station 3

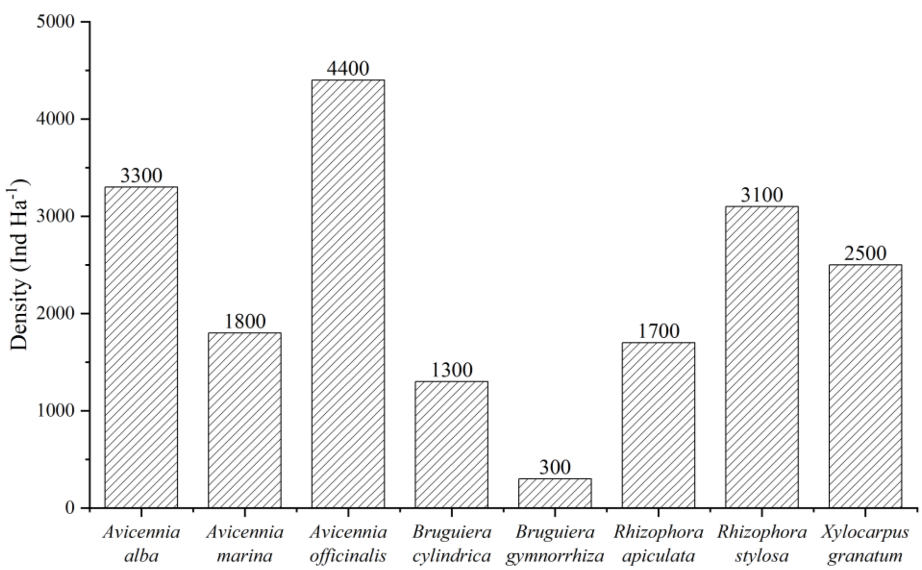

Fig. 6. Mangrove density at Station 4

Overall, spatial differences in species density across stations highlight the combined influence of local ecological conditions and anthropogenic pressure. *R. apiculata* dominance at Station 1 reflects estuarine colonization processes, while the repeated dominance of *A. officinalis* at Stations 2 and 3 underscores its ecological resilience and adaptive capacity. Station 4, with its higher density and species richness, likely represents a semi-natural mangrove forest with greater regenerative capacity and enhanced ecological stability. The reported density values represent the total counts obtained from the sum of mangrove densities across all measured categories, namely seedlings, saplings, and trees at each station.

The assessment of mangrove degradation criteria in Perupuk Village, based on the number of stands per hectare, revealed substantial variation across different growth categories. For the tree category, stand density ranged from 6,700 to 12,000 ind ha^{-1}, with a mean value of 8,600 ind ha^{-1}, which falls within the "good" classification. The sapling category exhibited densities between 1,000 and 4,200 ind ha^{-1}, with a mean of 2,050 ind ha^{-1}, also classified as "good." Seedling density ranged from 1,500 to 2,300 ind ha^{-1}, with a mean of 1,950 ind ha^{-1}, likewise meeting the criteria for "good" condition. When considered across all four observation stations, the overall mean stand density increased from 9,600 ind ha^{-1} at Station 1 to 18,400 ind ha^{-1} at Station 4. According to the Decree of the Minister of Environment No. 201 of 2004, mangrove condition is categorized into several levels based on vegetation density, and the results obtained in Perupuk Village consistently fall into the "good" category across all growth stages. These findings indicate that the mangrove ecosystem in Perupuk Village remains relatively healthy, with minimal signs of degradation. The consistently high values across seedlings, saplings, and trees confirm that all growth categories meet the "good" threshold under the established criteria, suggesting robust regeneration potential and ecological stability that underscore the resilience of the mangrove forest under prevailing environmental and anthropogenic conditions (Table 3).

Table 3. Standard criteria for mangrove degradation

Category	**Number of Stands (ind ha^{-1})**				**Average**	**Criteria**
	St. 1	**St. 2**	**St.3**	**St.4**		
Tree	6,700	6,800	8,900	12,000	8,600	Good
Sapling	1,400	1,600	1,000	4,200	2,050	Good
Seedling	1,500	1,800	2,300	2,200	1,950	Good
Average	9,600	10,200	12,200	18,400		

A comparative assessment of total mangrove abundance across the four stations (Stations 1 through 4) reveals clear spatial heterogeneity in stand density and community structure. At Station 1, the cumulative density of mangrove individuals (summing seedlings, saplings, and trees) was the lowest, approximately 9,600 ind ha^{-1}, whereas Station 4 exhibited the highest total abundance, around 18,400 ind ha^{-1}. Stations 2 and 3 displayed intermediate values, delineating a gradient of increasing mangrove density from Station 1 to Station 4. This trend suggests that Station 4 likely offers more favorable ecological conditions—such as reduced anthropogenic disturbance, greater sediment stability, optimal salinity and nutrient availability, and improved hydrological connectivity—that enhance regeneration, survival, and structural development across life stages. In contrast, the relatively low abundance at Station 1 may reflect stronger anthropogenic pressures, edge effects, or ecological constraints such as substrate instability and salinity fluctuations. According to **Carugati *et al.* (2018)**, mangrove degradation significantly reduces biodiversity, biomass, and ecosystem functioning, with direct consequences for stand density and vegetation structure. This perspective reinforces the interpretation that spatial differences in total mangrove abundance in Perupuk Village reflect the combined influence of ecological resilience and anthropogenic pressure.

3. Relative density, relative frequency, and importance value index (IVI)

The values of relative density, relative frequency, and IVI obtained from the computation of vegetation parameters for mangrove species at each station are presented in Fig. (7). Across the four sampling stations, the distribution of relative density (RD), relative frequency (RF), and importance value index (IVI) highlighted notable differences in species composition and ecological significance. At Station 1, *R. apiculata* exhibited clear dominance (RD = 43.69 %, RF = 44.51 %, IVI = 88.20), while *Avicennia marina* (IVI = 49.61), *R. mucronata* (38.30), and *R. stylosa* (23.90) played secondary roles. In Station 2, *A. officinalis* was the most influential species with RD = 34.30 %, RF = 37.89 %, and IVI = 72.19, supported by moderate contributions from *A. marina* (45.30) and *R. apiculata* (40.17). Lesser values were observed in *A. alba* (24.89) and *R. stylosa* (17.45). Station 3 showed greater richness, with seven species present. *A. officinalis* again ranked highest (IVI = 67.81), followed by *A. alba* (49.32) and *A. marina* (30.30), while *R. mucronata* was nearly absent (IVI = 1.46). At Station 4, the community was most diverse, including eight species. *A. officinalis* retained its dominance (IVI = 56.85), but *A. alba* (37.15), *R. stylosa* (32.48), and *X. granatum* (26.87) also contributed significantly. Meanwhile, *B. cylindrica* (11.82), *B. gymnorrhiza* (3.75), and *R. apiculata* (14.89) had lower values.

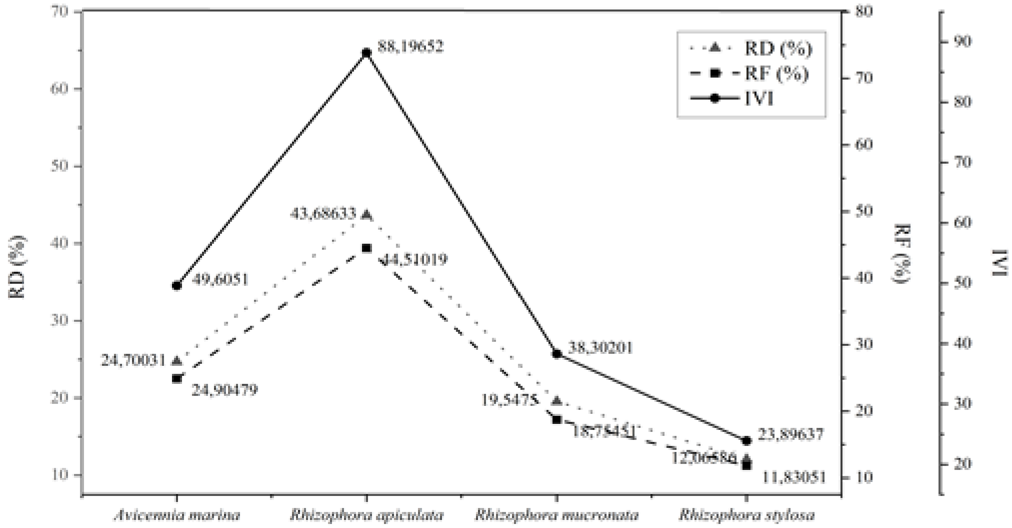

Fig. 7. Mangrove relative density, relative frequency, and IVI at Station 1

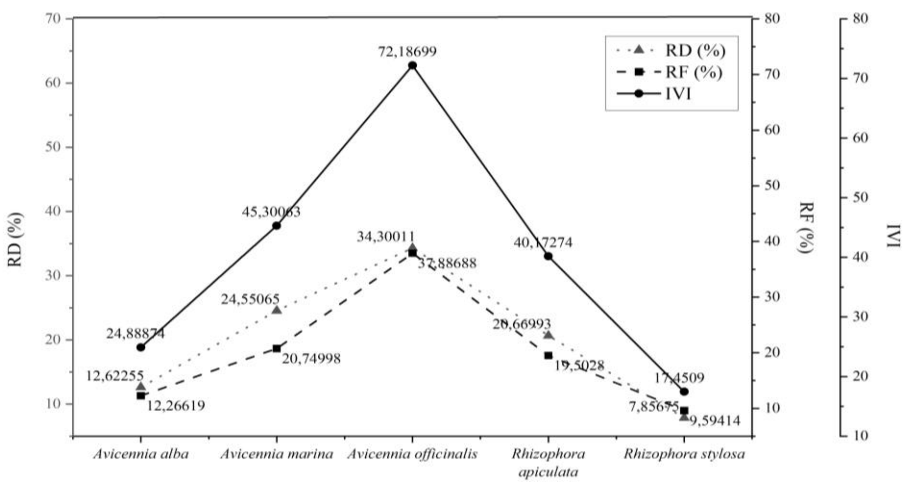

Fig. 8. Mangrove relative density, relative frequency, and IVI at Station 2

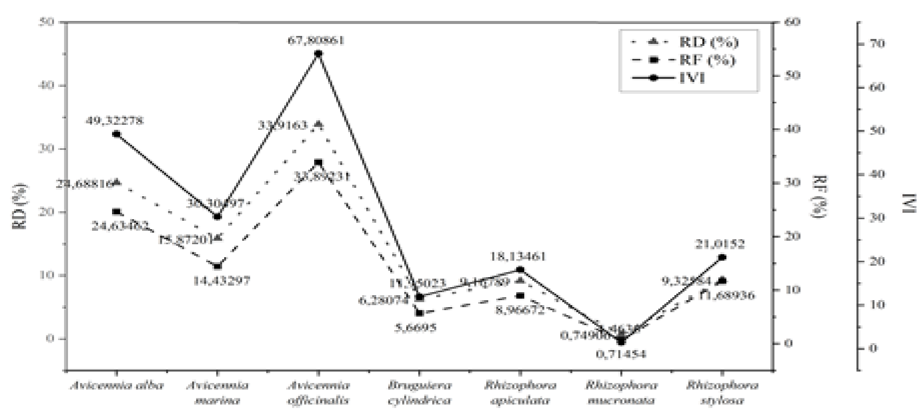

Fig. 9. Mangrove relative density, relative frequency, and IVI at Station 3

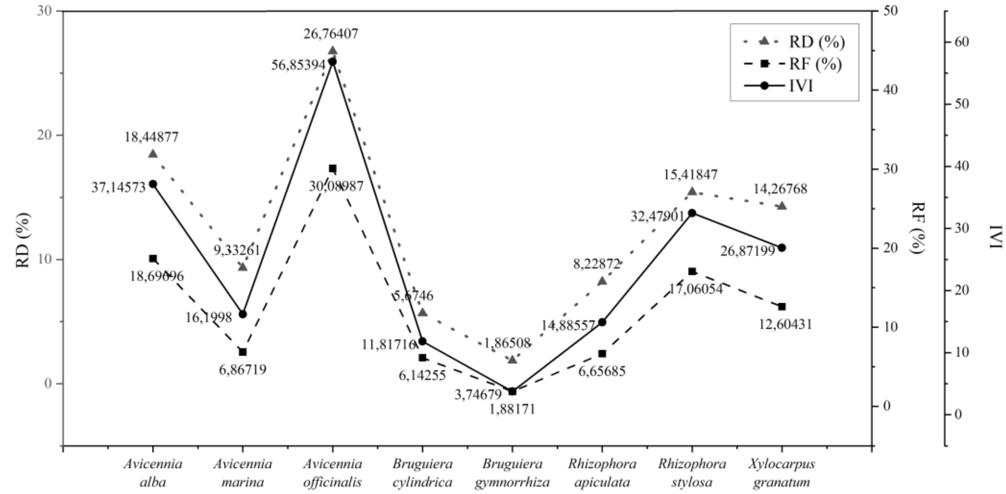

Fig. 10. Mangrove relative density, relative frequency, and IVI at Station 4

The recurring dominance of *A. officinalis* across three stations illustrates the ecological plasticity of *Avicennia* species, which are often pioneers in disturbed or transitional zones **(Karniati *et al.*, 2021)**. Conversely, the prevalence of *R. apiculata* at Station 1 reflects its adaptation to muddy estuarine substrates and strong tidal influence, conditions where *Rhizophora* typically thrives **(Nagelkerken *et al.*, 2008)**. The more balanced IVI values at Station 4 indicate a structurally complex community, consistent with observations that mixed mangrove stands exhibit greater resilience and ecological stability compared to monospecific stands **(Murdiyarso *et al.*, 2015)**.

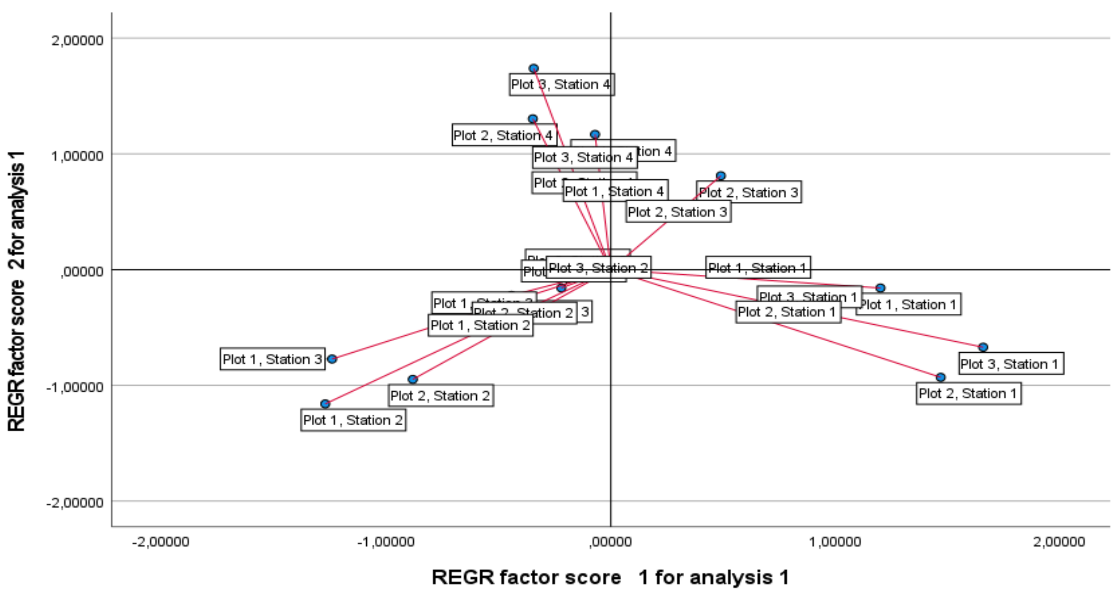

Fig. 11. PCA ordination plot showing the variation and grouping of mangrove vegetation structure across sampling plots

The PCA ordination shows distinct variation in mangrove community structure among stations based on IVI values per plot. Plots from Station 1 cluster tightly along the positive side of PC1, indicating relatively uniform species composition and consistent dominance patterns. Plots from Station 2 appear more widely dispersed along PC1 on both sides of the axis, reflecting greater heterogeneity in vegetation structure within the station. Plots from Station 3 are positioned near the center of the ordination space with slight extension toward positive PC1 and marginal negative PC2, suggesting a balanced mangrove assemblage without strong dominance by a single taxon. Plots from Station 4 are located mainly in the positive quadrant of both PC1 and PC2, demonstrating a more variable community structure and differences in species prevalence relative to the other stations. This pattern corresponds to the ability of ordination methods to reveal gradients in mangrove community composition and to distinguish ecological groupings along multivariate axes (**Dahdouh-Guebas *et al.*, 2002**). The graphical separation of plots also reflects how structural and compositional differences in mangrove stands can be represented in ordination space when species importance values vary across sampling units (**Wang *et al.*, 2004**).

4. Shannon–Wiener diversity index (H’) and evenness index (J’)

The Shannon–Wiener diversity index (H′) ranged from 0.579 to 1.120 across the four stations. Most stations exhibited low species diversity, while Station 3 showed a moderate level of diversity, indicating a relatively more varied mangrove composition compared to the other stations.

Evenness values (J′) ranged from 0.014 to 0.030, reflecting very low species evenness throughout the study area. This pattern suggests that mangrove communities at all stations are dominated by a few species, resulting in an unbalanced distribution of individuals among species. The dominance structure indicates limited community uniformity, which is typical of mangrove ecosystems where certain species adapt better to specific site conditions and outcompete others.

Table 4. Shannon–Wiener diversity index (H’) and evenness index (J’) at each station

Station	H′ (Shannon)	Category (H′)	J′ (Evenness)	Category (J′)
Station 1	0.402083333	Low	0.019	Very low
Station 2	0.45625	Low	0.017	Very low
Station 3	1.120	Moderate	0.030	Very low
Station 4	0.579861111	Low	0.014	Very low

5. Habitat quality assessment

The water quality measurements across four observation stations showed relatively consistent conditions with some local variation. Temperature ranged between 33.10 and

33.60°C, values slightly above the optimal range generally reported for tropical mangroves, yet still within tolerance limits for most species. Such elevated temperatures can affect metabolic balance but mangroves are known to withstand short-term fluctuations in thermal regimes **(Quisthoudt *et al.*, 2013)**.

The pH values varied from 6.67 to 7.41, spanning slightly acidic to near-neutral conditions. These values remain within the acceptable range for mangrove ecosystems, where soil and water pH between 6 and 8 are favorable for seedling establishment and nutrient cycling **(Dookie *et al.*, 2022)**. The lowest value observed at Station 1 (6.67) may reflect organic matter decomposition and acidification processes typical of muddy mangrove soils.

Salinity measurements in Perupuk Village ranged from 21.87 to 22.24 ‰. This value lies within a moderate range that can still support mangrove growth, although it may already impose stress on salt-sensitive species. According to **Krauss *et al.* (2008)**, mangroves demonstrate broad physiological tolerance and are capable of surviving in salinities up to 30–40 ‰, but higher salinity levels generally reduce growth rates, limit seedling establishment, and constrain forest regeneration. The recorded values in Perupuk Village therefore remain ecologically acceptable for mangrove persistence, yet they indicate conditions slightly outside the most commonly cited optimal range of 5–20 ‰ for maximum growth performance.

Substrate analysis confirmed that all stations were dominated by muddy sediments. Such substrates enhance water retention, nutrient storage, and anchorage, supporting seedling recruitment and resilience of mature trees. Muddy sediments are particularly important for pneumatophore and stilt root stability, and have been associated with higher mangrove regeneration success compared to sandy or rocky substrates **(Kathiresan, 2012)**.

Overall, the measured parameters indicate that the aquatic environment in Perupuk is generally suitable for mangrove growth. The near-neutral pH and stable salinity are favorable for community stability, while the muddy substrate provides physical and nutritional support. However, the relatively high water temperature requires monitoring as it may influence regeneration dynamics and species composition under climate change scenarios.

Table 5. Mangrove habitat condition in Perupuk Village

No	Parameter	Results			
		S1	**S2**	**S3**	**S4**
1	Temperature (°C)	33.30	33.20	33.10	33.60
2	pH	6.67	6.97	7.41	7.37
3	Salinity	22.24	21.93	21.96	21.87
4	Sediment	Muddy substrate	Muddy substrate	Muddy substrate	Muddy substrate

The habitat assessment conducted in Perupuk Village using the modified matrix of **Sudarso (2013)** resulted in total scores of 34 at Station 1, 31 at Station 2, 33 at Station 3, and 35 at Station 4 (Table 9). According to the **US-EPA (1999)** classification thresholds (36–44 = optimal; 27–35 = sub-optimal; 18–26 = marginal; <18 = poor), all four stations fall into the sub-optimal category. This indicates that while the mangrove stands are structurally functional, they are constrained by several ecological and anthropogenic factors.

High canopy cover and mangrove density (scores 3–4) supported stable stands across sites. However, tree height consistently scored the lowest (1) at all stations, reflecting limited vertical development. Structural attributes such as tree height are important because taller mangroves provide greater habitat complexity and ecological services, yet growth can be suppressed under environmental stressors **(Alongi, 2020)**. Vegetation formation was dominated by *Rhizophora* at stations 1–2 and *Avicennia* at stations 3–4, but irregular structure reduced overall habitat quality.

The most limiting factor was sediment deposition, which scored 1 across all stations due to heavy inputs and turbidity >100 NTU. Sediment stress is recognized as a major threat to mangrove ecosystems because excessive burial reduces root oxygenation and seedling survival **(Rovai *et al.*, 2018)**. Additionally, disturbance factors such as plastic waste and human activity were observed at all stations (score 2), consistent with evidence that anthropogenic pressures like pollution and land conversion reduce mangrove resilience **(Friess *et al.*, 2019)**.

According to the disturbance protocol of **US-EPA (1999)**, habitat condition is closely tied to visible human impacts such as vegetation removal, waste, and substrate alteration. Stations 1 and 2 were most affected by disturbance, while Station 4, despite having the highest score, remained below the optimal threshold because of persistent sediment and disturbance pressures. These findings mirror global trends showing that sediment instability and human interference are key drivers of mangrove habitat decline **(Goldberg *et al.*, 2020)**.

Table 6. Criteria for mangrove habitat quality

Station	Total Score	Habitat Criteria
1	34	Sub-optimal
2	31	Sub-optimal
3	33	Sub-optimal
4	35	Sub-optimal

6. Mangrove area coverage

The spatial analysis using ArcGIS Pro and NDVI-based classification indicated that the mangrove ecosystem in Perupuk Village covered an area of 45.17 hectares (Fig. 7). This area was distributed across density classes: low density 0.81 ha, sparse density 8.87

ha, medium density 1.63 ha, moderate density 13.79 ha, and high density 20.28 ha. The classification highlights that more than 44% of the mangrove area falls under the high-density category, while smaller portions are distributed in sparse and low-density zones.

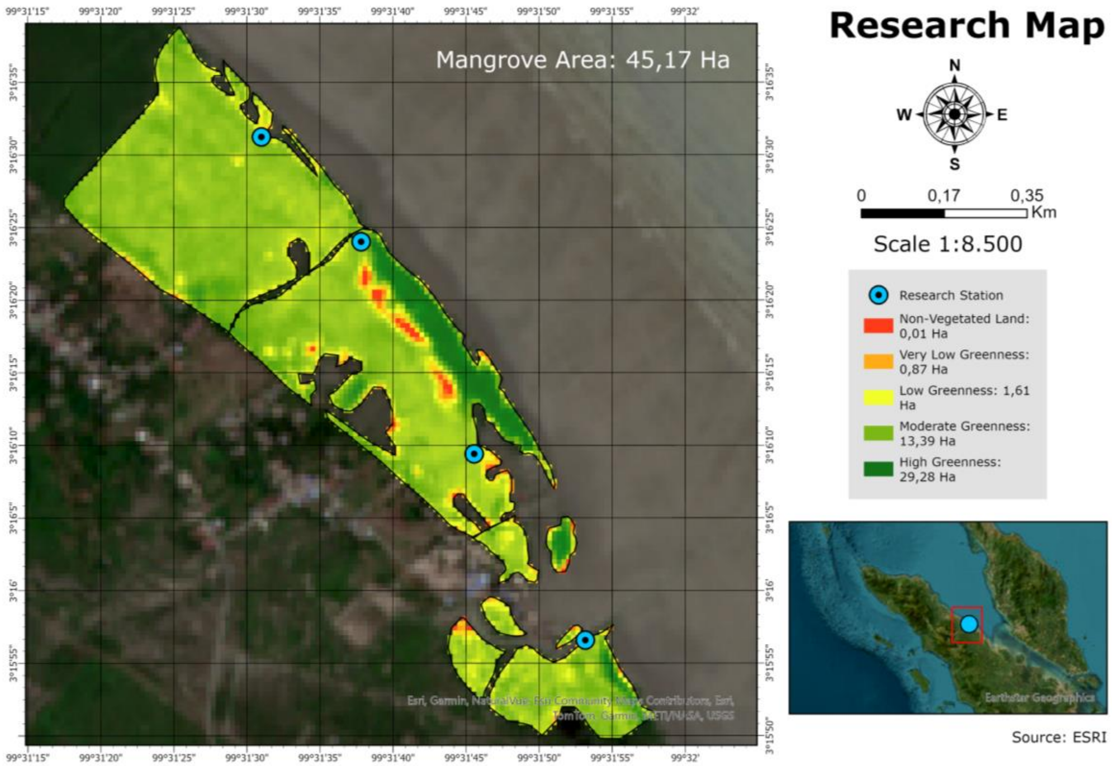

Fig. 12. Estimated map of the mangrove area of Perupuk Village

The heterogeneity in mangrove density reflects both natural ecological processes and anthropogenic pressures. Dense stands were concentrated in less disturbed intertidal zones, whereas low-density stands were mainly associated with areas exposed to human activity and sedimentation. Similar patterns were observed in Southeast Asia, where dense mangroves persisted in protected zones, while degraded stands were linked to conversion and local disturbance **(Richards & Friess, 2016**). The spatial distribution in Perupuk suggests that management should prioritize sparse and low-density areas, as these zones are most vulnerable to further degradation. Strengthening community-based rehabilitation in these areas could potentially increase the proportion of dense mangrove cover, contributing to greater ecosystem resilience and carbon storage capacity.

DISCUSSION

The importance value index (IVI) analysis showed that *R. apiculata* consistently dominated at several stations, while *Avicennia* species were more prominent in others. Species with high IVI values are considered ecologically important because they contribute substantially to forest structure and stability. As it was explained by **Adame *et***

***al.* (2014)**, species dominance within mangrove communities reflects ecological functions such as sediment trapping and carbon storage, which are critical for sustaining ecosystem resilience. This indicates that the observed dominance of *R. apiculata* in Perupuk plays a central role in maintaining sediment stabilization and shoreline protection. The PCA reveals clear structural differentiation among mangrove stations, with plots within each station clustering closely and those among stations separating along PC1 and PC2, indicating consistent species dominance patterns internally and distinct ecological conditions across sites. This pattern reflects variation in habitat characteristics and species responses to environmental gradients rather than random spatial arrangement. According to **Dahdouh-Guebas *et al.* (2002)**, ordination is effective in distinguishing mangrove community structure along ecological gradients, highlighting clusters driven by vegetation dynamics and site conditions. According to **Wang *et al.* (2004)**, segregation of plots in multivariate space represents species-specific responses to habitat heterogeneity in mangrove ecosystems, supporting the observed separation in this study.

Shannon–Wiener diversity values in this study indicate relatively low to moderate mangrove diversity across stations, with the highest value observed at Station 3 and the lowest at Station 1. This pattern reflects differences in stand structure, where mixed stands of *Avicennia*, *Rhizophora*, and *Bruguiera* at Station 3 promote higher species diversity, while the dominance of one or two species at other stations reduces community complexity. According to **Akhmadi *et al.* (2023)**, greater structural heterogeneity in mangrove stands is typically associated with higher Shannon values due to enhanced niche availability and reduced competitive exclusion. Evenness values across stations were low, demonstrating strong dominance by a few taxa such as *Avicennia marina* and *Rhizophora apiculata*. Similar findings were reported by **Ashari *et al.* (2019)**, who noted that low evenness in mangrove communities commonly arises when pioneer species outcompete others under fluctuating coastal conditions. Moderate diversity with low evenness in this study suggests that the ecosystem is functioning but may be undergoing competitive pressure and regeneration dynamics associated with local environmental stress and selective species adaptation.

Habitat quality scores across all stations were categorized as sub-optimal, reflecting moderate levels of anthropogenic disturbance, sedimentation, and waste accumulation. Sub-optimal conditions highlight the vulnerability of the ecosystem to further degradation if pressures persist. **Osland *et al.* (2022)** demonstrated that mangrove ecosystems under intermediate disturbance regimes often exhibit reduced regeneration capacity and altered species composition, which may compromise their long-term ecological services. The presence of abundant plastic waste and high turbidity in Perupuk suggests that without intervention, ecosystem recovery potential may decline.

Remote sensing analysis using NDVI revealed both stable and declining mangrove coverage in certain areas. Declines in NDVI values correspond to reduced canopy density, which can be linked to anthropogenic activities such as land conversion and excessive harvesting. According **to Goldberg *et al.* (2020)**, human-driven mangrove loss remains the dominant driver of canopy decline globally, surpassing natural factors. Integrating spatial analysis with field-based ecological assessment therefore provides a more comprehensive perspective on the state of the ecosystem.

From a conservation standpoint, the combination of IVI results, sub-optimal habitat scores, and NDVI-based coverage estimates underscores the need for targeted restoration and management. As recommended by **Worthington *et al.* (2020)**, effective mangrove management requires aligning ecological indicators with conservation strategies that address both local disturbances and broader climate adaptation objectives. For Perupuk Village, this means prioritizing waste management, enforcing land-use regulations, and supporting community-based rehabilitation initiatives to improve habitat quality and secure long-term ecosystem services.

CONCLUSION

Nine mangrove species were recorded in Perupuk Village, namely *A. alba*, *A. marina*, *A. officinalis*, *B. cylindrica*, *B. gymnorrhiza*, *R. apiculata*, *R. mucronata*, *R. stylosa*, and *X. granatum*. Species composition and structural parameters varied across stations, with *R. apiculata* showing the highest importance value index (IVI) values at Station 1, while *A. officinalis* dominated at stations 2 and 3, and *A. alba* and *R. stylosa* contributing significantly at Station 4. Habitat quality assessment categorized all stations as sub-optimal, with total scores ranging from 31 to 35, constrained primarily by sediment deposition and anthropogenic disturbances. Shannon–Wiener diversity values indicated low to moderate diversity ($H' = 0.58–1.12$) and low evenness ($J' = 0.01–0.03$), reflecting community dominance by a few species and uneven distribution among taxa. Remote sensing analysis estimated the mangrove ecosystem area at 45.17 ha, dominated by high-density stands but with considerable portions of low and sparse density zones. These findings highlight the ecological significance of Perupuk's mangroves while emphasizing the need for targeted management to reduce disturbance, stabilize sediments, and support community-based rehabilitation.

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